Constellation-X Studies of Supernova Radioactivity

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NASA theme: *Life Cycles of Matter*

Major supernova questions:

1. What are SNe Ia?

   The nature of thermonuclear explosions is best seen in burning products?

2. What is the core-collapse mechanism?

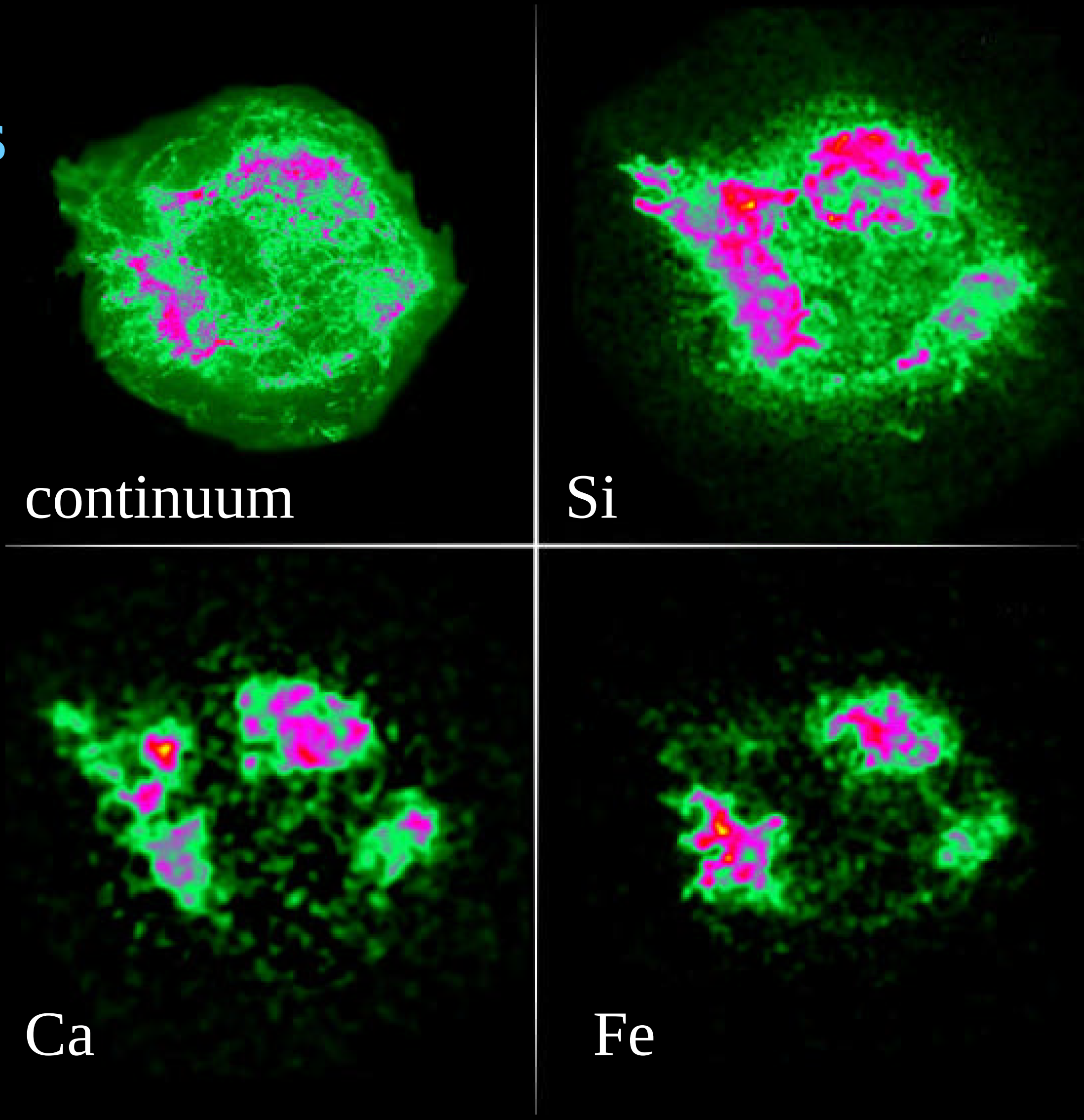
   Several radionuclides among last matter ejected.

X-ray Spectroscopy reveals nucleosynthesis products in supernova remnants

Detailed imaging, spectroscopy yield kinematics of different zones…

However,
- only elemental abundances
- new vs. old?
- complicated ionization & excitation conditions

Quantitative nucleosynthesis yields difficult to derive



Cas A from Chandra, Hwang et al.

Gamma-Ray Line Studies of Radioactivity

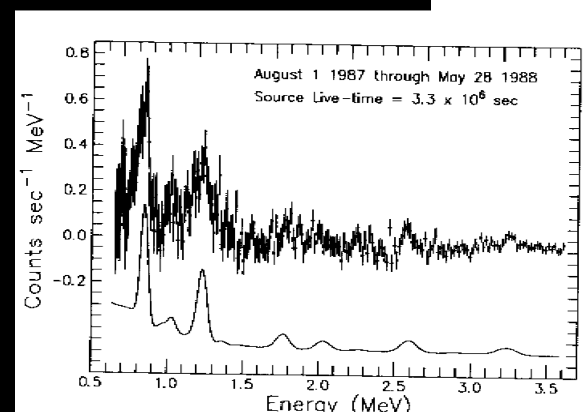
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Provides direct count of newly created nuclei

- in individual explosions (shorter $\tau_{1/2}$)
- global galactic production (longer $\tau_{1/2}$)

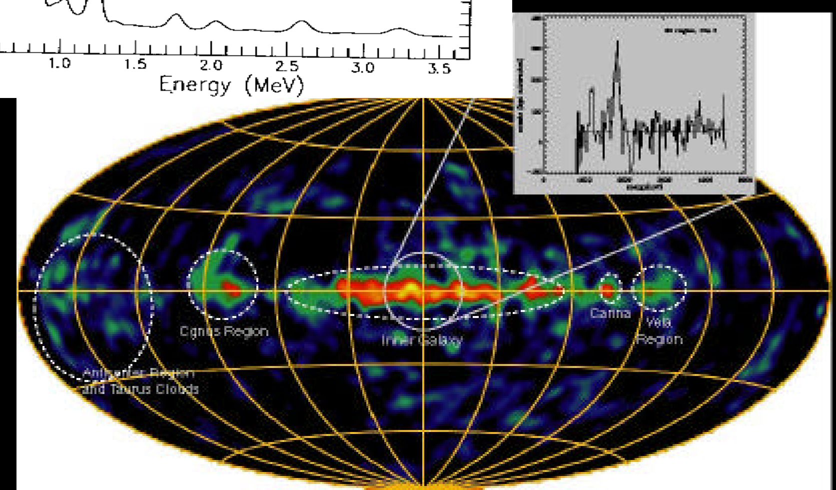
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

e.g., ^{26}Al from Milky Way
^{56}Co & ^{57}Co from SN 1987A
^{44}Ti from Cas A



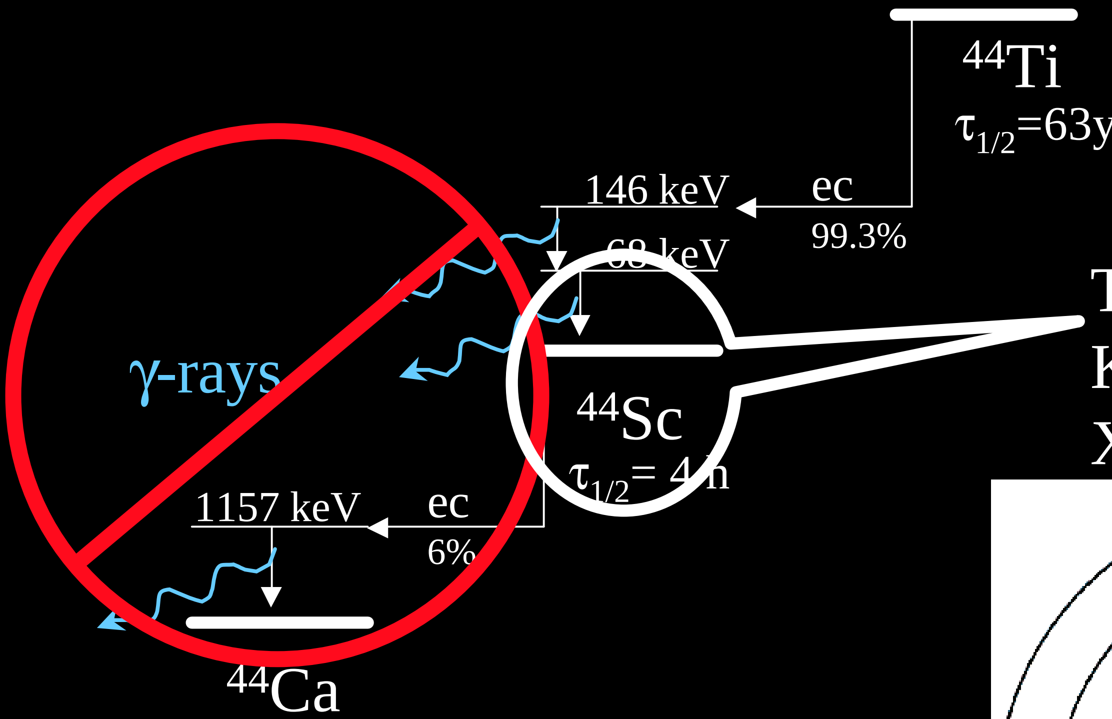
However,

- small effective areas
  (no focusers/concentrators yet)
- poor angular resolution
- notoriously difficult backgrounds
- few flight opportunities

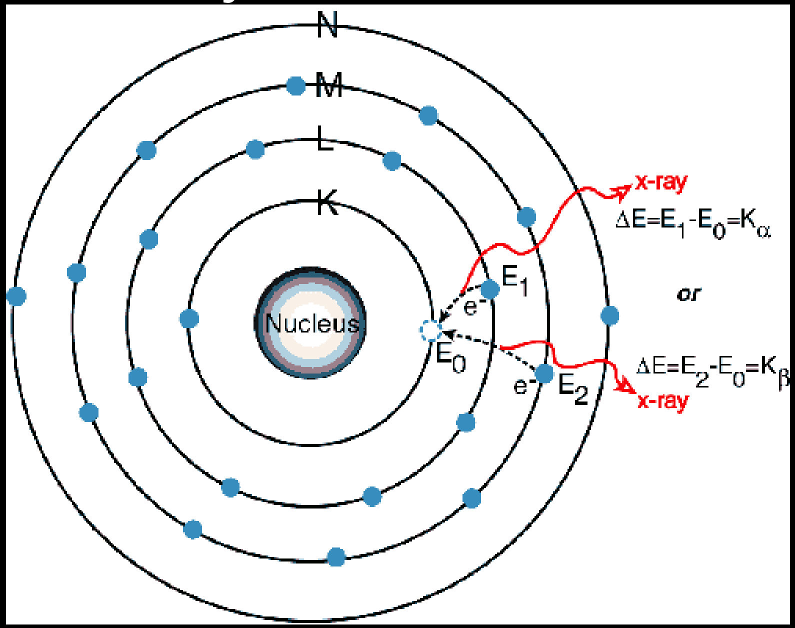


Same science, another way…

Example decay: ^{44}Ti



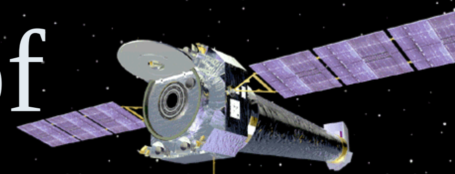
This atom formed with K-shell vacancy -- Sc K_α X-rays emitted.

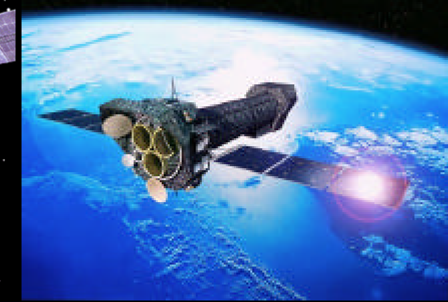


Note: we can hope to see the decay Sc K_α line over stable Sc line (re: Ca K_α) because X(Sc) ~ X(Ca)/2000

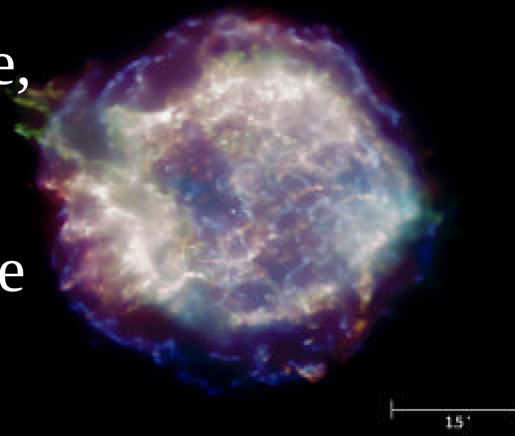
Ni50
Ni51
Ni52 38 ms 0+ ECp
Ni53 45 ms (7/2-) ECp
Ni54 0+ EC
Ni55 212.1 ms 7/2- EC
Ni56 6.077 d 0+ EC
Ni57 35.60 h 3/2-
Ni59 7.6E+4 y 3/2- EC
Co49
Co50 ECp
Co51
Co52 18 ms EC
Co53 240 ms (7/2-) EC
Co54 193.23 ms 0+ EC
Co55 17.53 h 7/2- EC
Co56 77.27 d 4+ EC
EC
Fe48 44 ms ECp
Fe49 (7/2-) ECp
Fe50 150 ms 0+ ECp
Fe51 305 ms (5/2-)
Fe52 8.275 h 0+
Fe53 8.51 m 7/2-
Fe55 2.73 y 3/2- EC
Z
Mn47 100 ms ECp
Mn48 ECp,ECα,...
Mn49 382 ms
Mn53 3.74E+6 y 7/2- EC
2.2
0.28
Mn56 2.5785 h 3+ β-
Mn57 85.4 s 5/2- β-
N
Cr46 0.26 s 0+ EC
Cr47 500 ms 3/2- EC
0+ EC
Cr55 3.497 m 3/2- β-
Cr56 5.94 m 0+ β-
Ti44 63 y 0+ EC
V51 7/2- 99.750
EC,β- 0.250
EC
V52 3.743 m 3+ β-
V53 1.61 m 7/2- β-
V54 49.8 s 3+ β-
V55 6.54 s (7/2-) β-
Ti47 5/2- 7.3
Ti48 0+ 73.8
Ti49 7/2- 5.5
Ti50 0+ 5.4
Ti51 5.76 m 3/2- β-
Ti52 1.7 m 0+ β-
Ti53 32.7 s (3/2)- β-
Ti54 0+
Sc46 83.79 d 4+ β-
Sc47 3.3492 d 7/2- β-
Sc48 43.67 h 6+ β-
Sc49 57.2 m 7/2- β-
Sc50 102.5 s 5+ β-
Sc51 12.4 s (7/2)- β-
Sc52 8.2 s 3+ β-
Sc53
Ca42 0+ 0.647
Ca43 7/2- 0.135
Ca44 0+ 2.086
Ca45 162.61 d 7/2- β-
Ca46 0+ 0.004
Ca47 4.536 d 7/2- β-
Ca48 6E+18 y 0+ β-,β-β- 0.187
Ca49 8.718 m 3/2- β-
Ca50 13.9 s 0+ β-
Ca51 10.0 s (3/2-) β-n
Ca52 4.6 s 0+ β-

X-ray Line Studies of Supernova Radioactivity





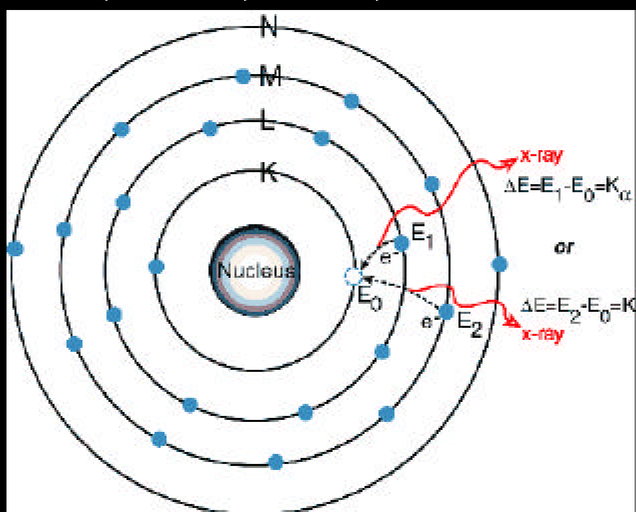
Many proton-rich nucleosynthesis products decay by electron capture, mostly leaving K-shell vacancy.



- + area
- + ang resolution
- + background
- - fov
- - continuum
- - absorption

Current X-ray spectrometers are more sensitive to lines than, e.g., INTEGRAL spectrometer is to narrow gamma-ray lines.

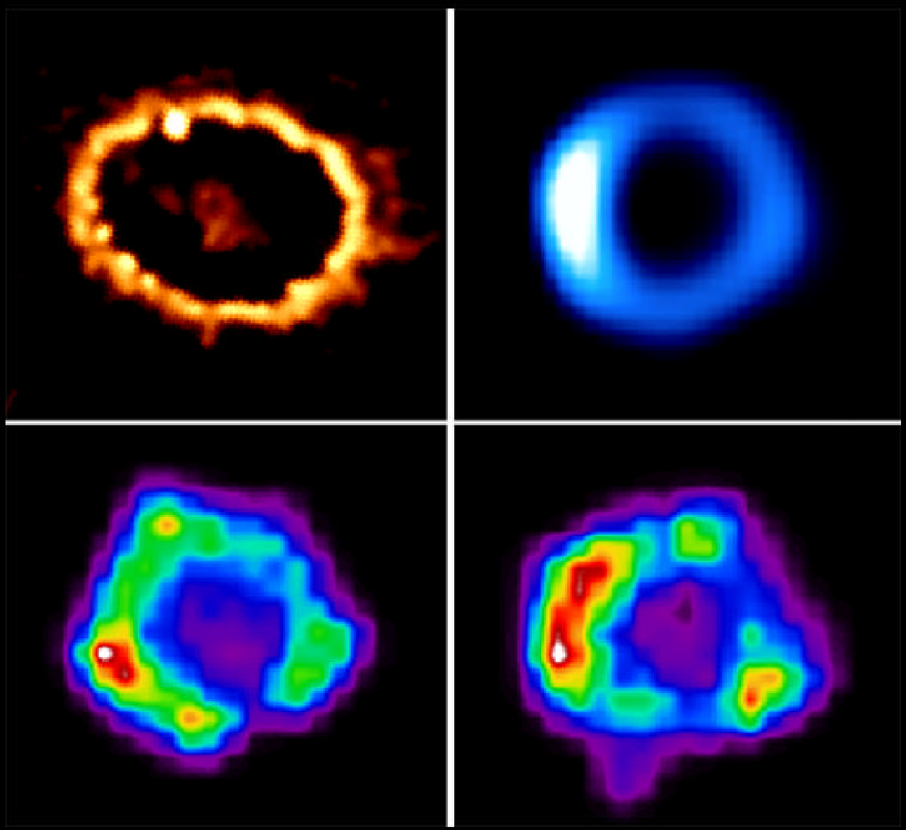
^{55}Fe, ^{59}Ni, ^{44}Ti, ^{53}Mn …



We can measure (and map) supernova nucleosynthesis products in SN, SNR, and the diffuse ISM in X-ray lines.

See also Leising (2001, 2002)

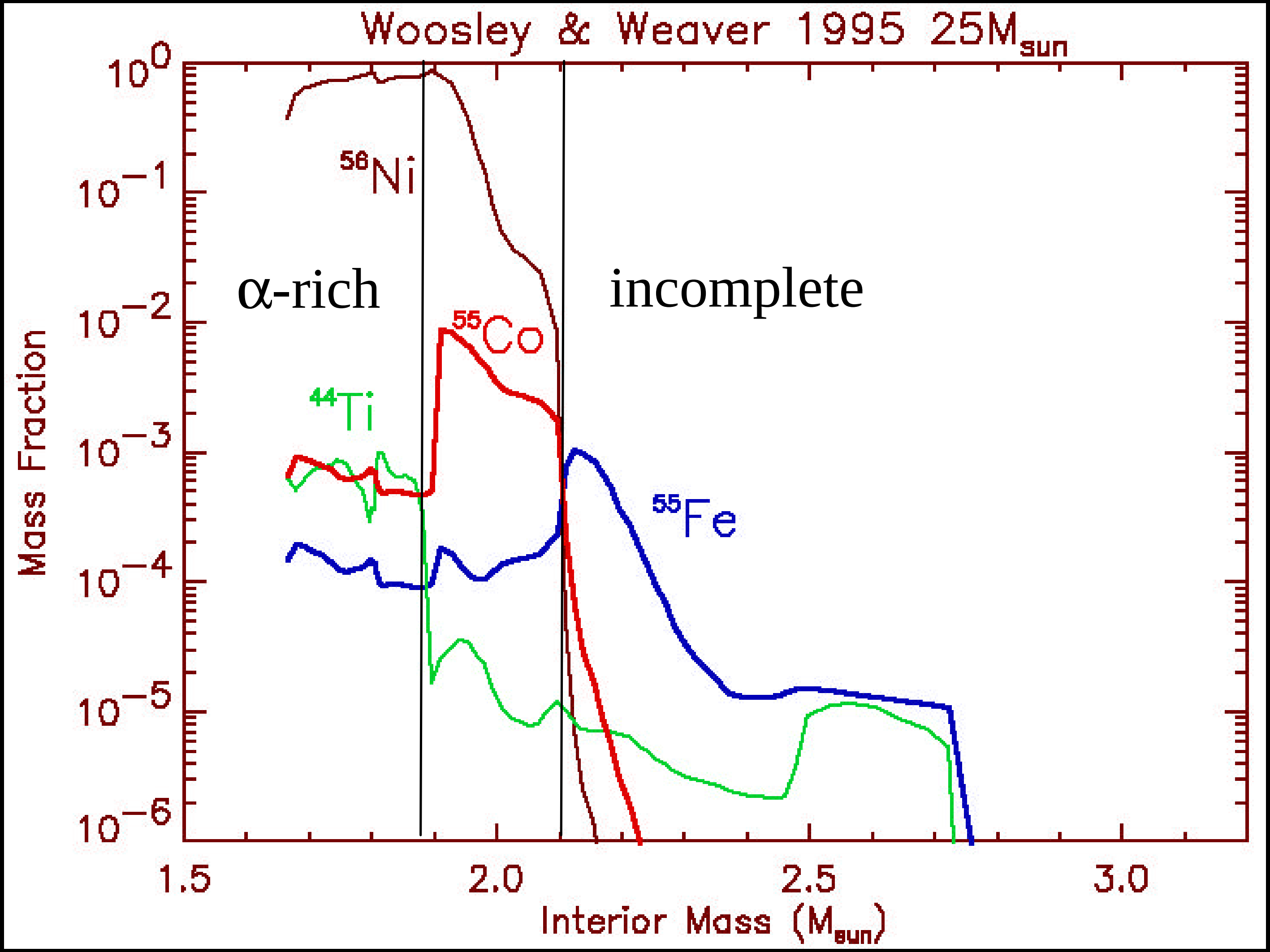
Radioactive ^{55}Fe X-rays as a Diagnostic of SN 1987A



A Probe of:

The nuclear burning conditions just outside the central core - a third isotope measured?

The ejection velocities and possible mixing of the intermediate mass zones



^{55}Fe is produced in normal freezeout NSE (as ^{55}Co) and in incomplete Si-burning near T = 3x10^9 K

[^{55}Co(p,γ)^{56}Ni is most important rate]

Ni55 212.1 ms 7/2- EC	Ni56 6.077 d 0+ EC	Ni57 35.60 h 3/2-	Ni58 0+ 68.077
Co54 193.23 ms 0+ * EC	Co55 17.53 h 7/2- EC	Co56 77.27 d 4+ EC	Co57 271.79 d 7/2- EC
Fe53 8.51 m 7/2- * EC	Fe54 0+ 5.8	Fe55 2.73 y 3/2- EC	Fe56 0+ 91.72
Mn52 5.591 d 6+ * EC	Mn53 3.74E+6 y 7/2- EC	Mn54 312.3 d 3+ EC,β^-	Mn55 5/2- 100

^{55}Fe ($\tau_{1/2}$ = 2.7 y) $\Rightarrow$ ^{55}Mn

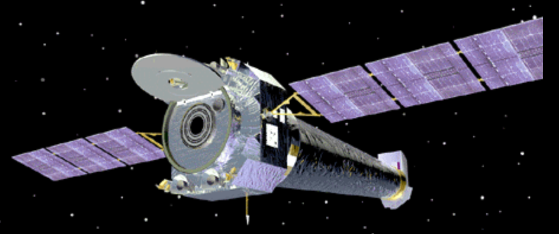
K_α 5.9 keV (24.4%)

- Source of ^{55}Mn in nature (most from ^{55}Co [$\tau_{1/2}$ = 18h]).
- Explosive Si-burning (NSE, also incomplete and ex-He).
- Core collapse SN, typically 1.3x10^{-3} $M_\odot$ [=f(Z)] (from models or Galactic chemical evolution)

  Still, $F_{SN\ 1987A} = 5\text{x}10^{-6}\ \text{cm}^{-2}\ \text{s}^{-1}$ (Z_{lmc}, τ=1)
- Type Ia models make (with great variety) $\geq 10^{-2}\ M_\odot$

  F (5.9 keV) = 7x10^{-6} (D/1 Mpc)$^{-2}$ cm^{-2} s^{-1}

Data and Analysis



Chandra ObsID 1967 (2000 Dec 7)

99 ksec ACIS S-3

(A_{eff}=235 cm^2, ΔE=130 eV)

See also Park et al. (2002)

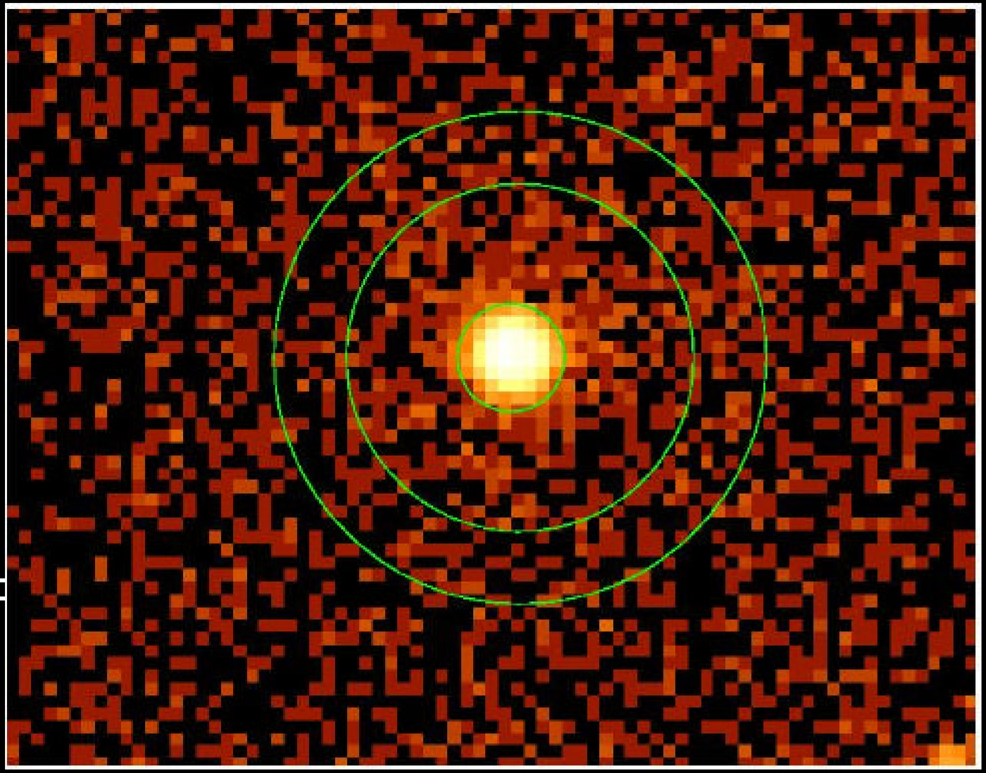
Penn State CTI correction

Ciao

Standard event filters

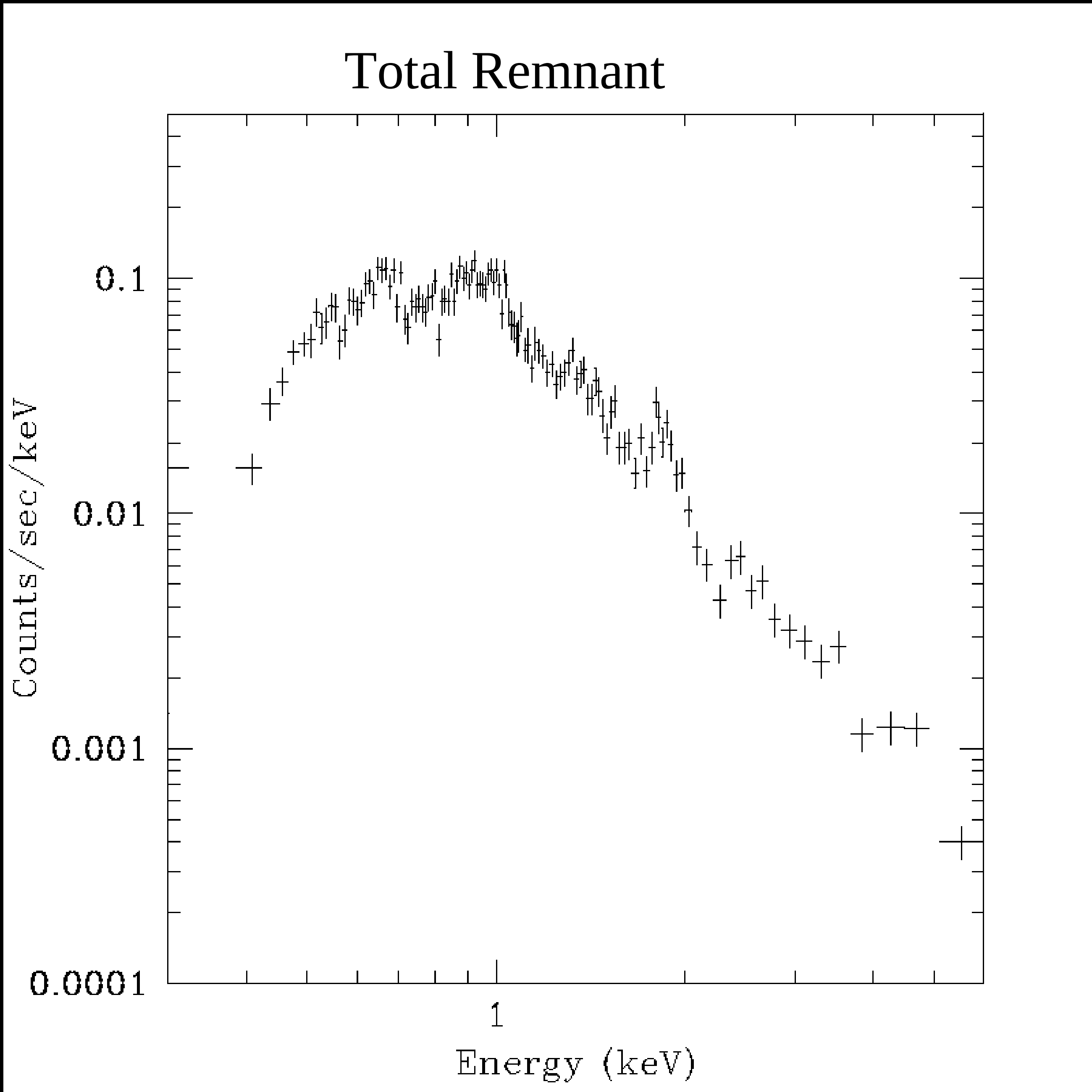
Source and

Background Regions=



psextract

Chandra ACIS Spectrum SN 1987A



See Michael et al. (2002)

Chandra ACIS SN 1987A Spectrum

No evidence of 5.9 keV line

Narrow line

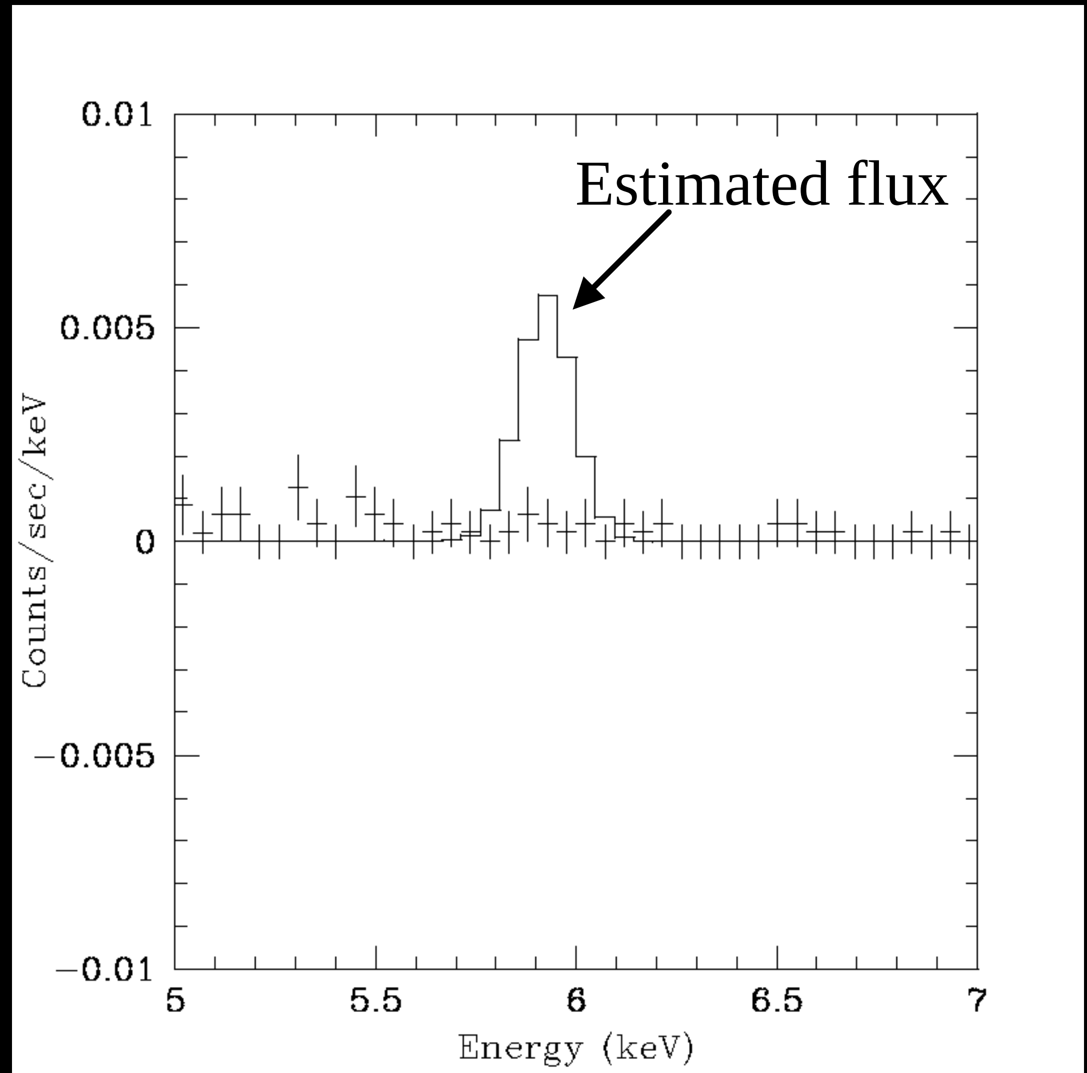
$F = (4.0 \pm 2.9) \times 10^{-7}\ cm^{-2}\ s^{-1}$

Upper limit to line flux

$F \leq 1.2 \times 10^{-6}\ cm^{-2}\ s^{-1}$ (99%)

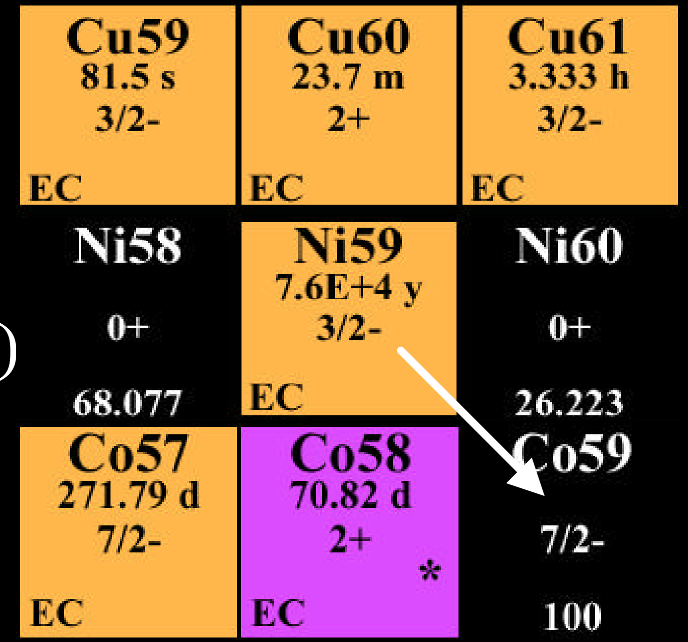
Similar limit from 41 ksec XMM-Newton EPIC-PN observation (can be improved?)

Explained by larger optical depth of mantle at 6 keV?

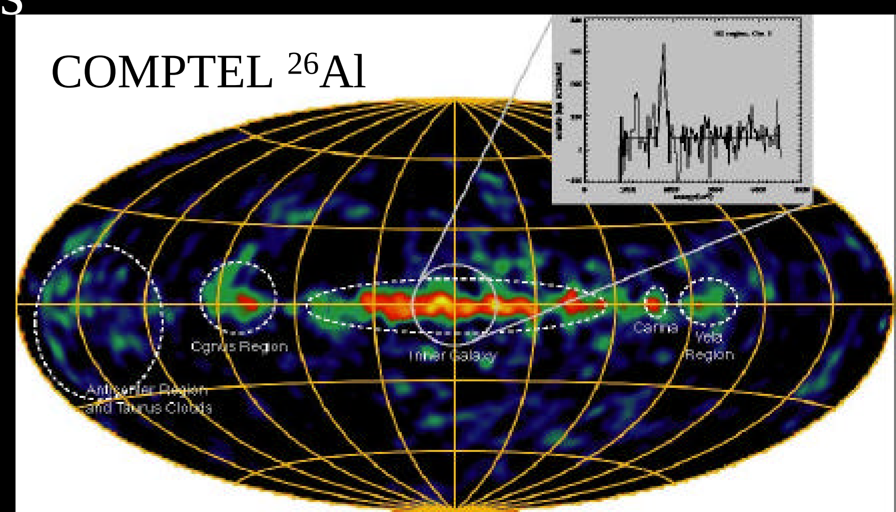


^{59}Ni ($\tau_{1/2}$ = 75 ky)

K_{α} 6.9 keV (29.9%)



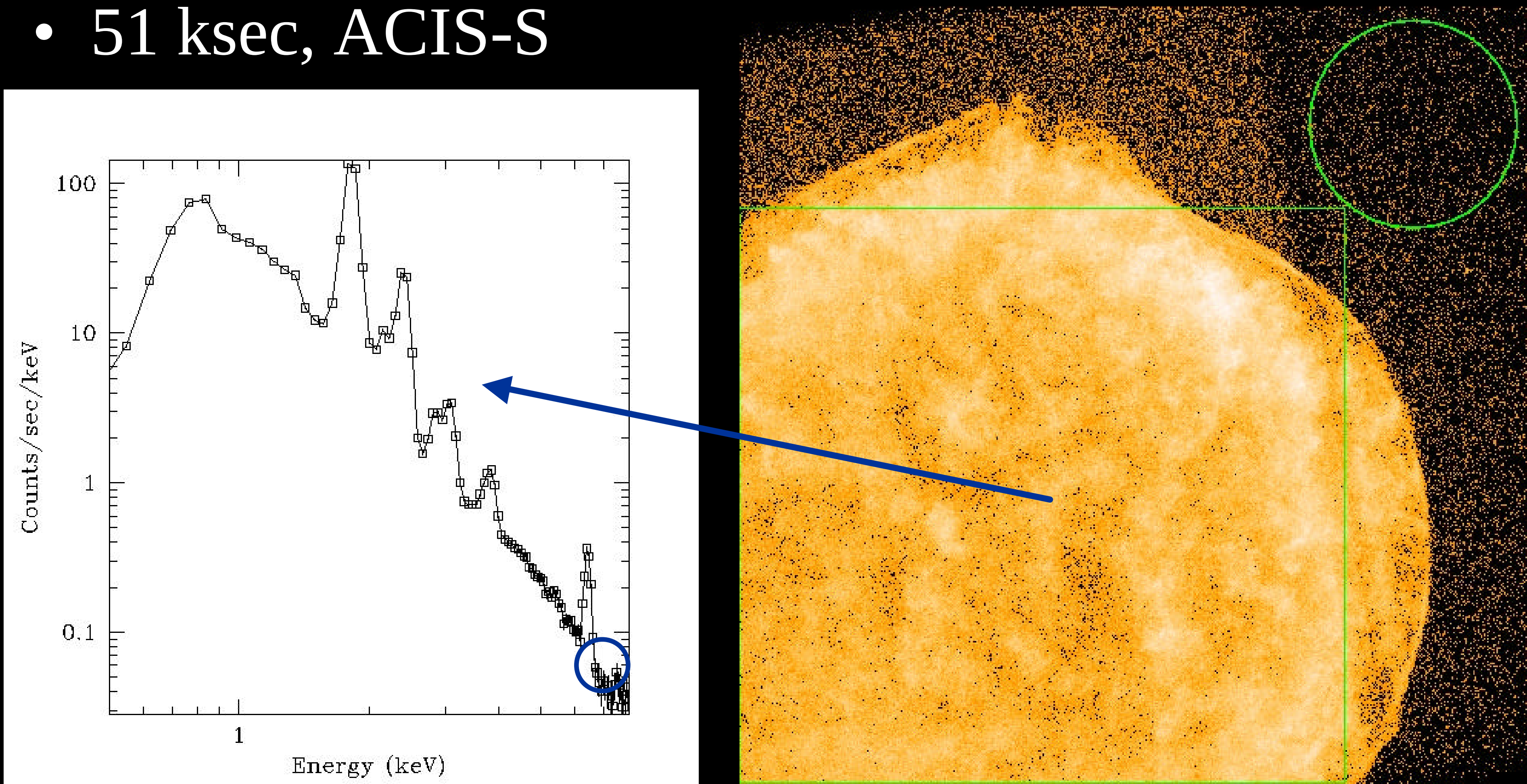
- Source of much ^{59}Co in nature (including ^{59}Cu)
- Cosmic Rays : clues to acceleration delays
- Core collapse SN, typically $2\text{x}10^{-4}$ $M_{\odot}$
  α-rich freezeout of NSE from inner ejecta
  --> 0.8 $M_{\odot}$ in ISM (patchy -- ~2700 SNR)
- Type Ia's make more ($\geq 10^{-3}$ $M_{\odot}$), possible bulge component.
- Type Ia SNR, $F_{Tycho} = 3\text{x}10^{-6}$ $cm^{-2}\,s^{-1}$
  (whole remnants) $F_{1006} = 5\text{x}10^{-6}$
- Together, diffuse flux
  central steradian = $3\text{x}10^{-4}$ $cm^{-2}\,s^{-1}$



Less smooth than ^{26}Al

Chandra Studies of ^{59}Ni in Tycho's SNR

- ObsID 115, 2000/09/20
- 51 ksec, ACIS-S

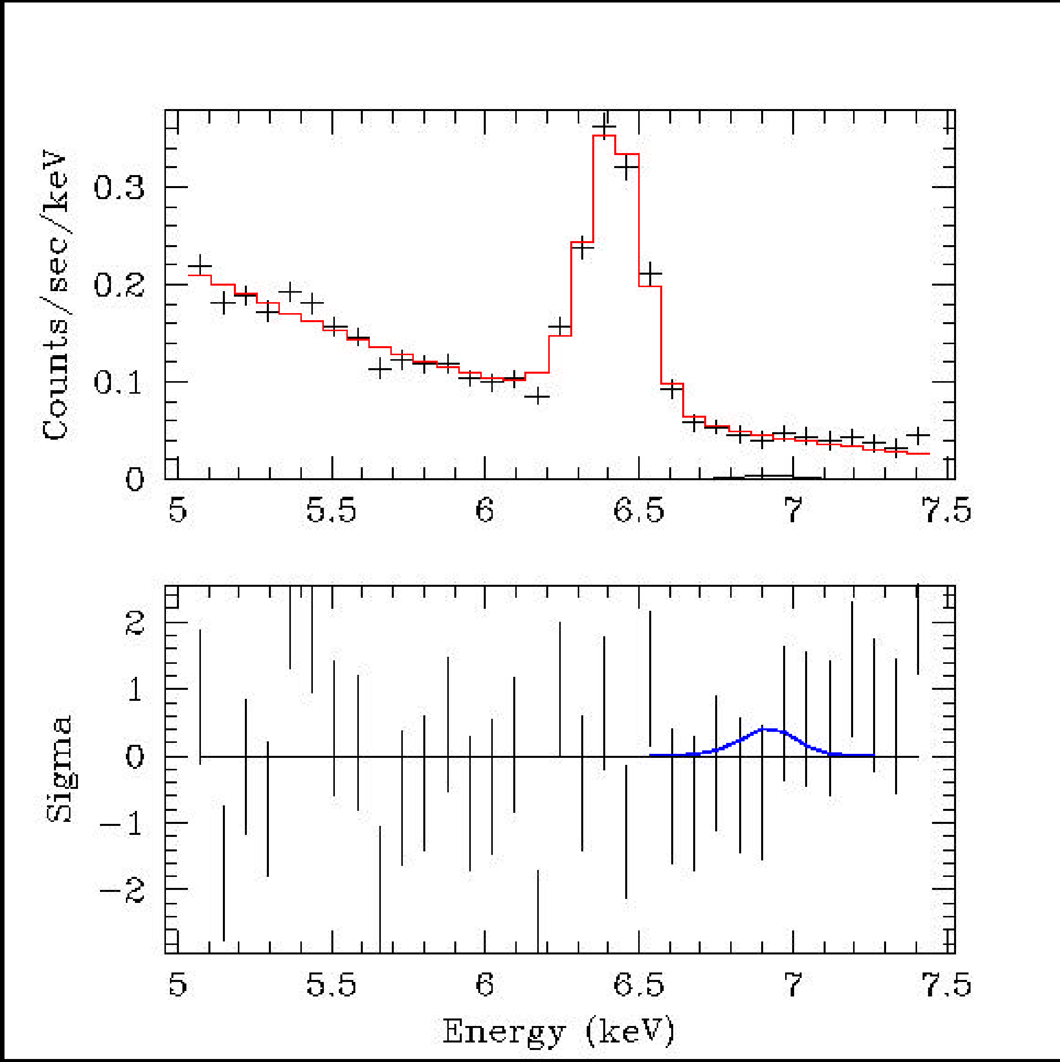


Chandra Tycho spectrum near Co-K_α

- Strong continuum and Fe-K_α
- No evidence for ^{59}Ni decay

F(6.9 keV) < 10^{-5} cm^{-2} s^{-1}
99%

- Sensitivity limited by statistics of continuum
- Better physical model of spectrum needed



Considerations for Constellation-X

A_{eff} (6 keV) *large* -- if ~6000 cm^2

Will measure ^{55}Fe in SN 1987A

and in SN Ia to 10 Mpc

Shorter-lived nuclei in SN Ia surfaces (if there.)

Good energy resolution to minimize bright continuum under lines

(helps only to Doppler broadening, $E/\Delta E \sim 300$)

Measure (map?) ^{59}Ni, ^{53}Mn in nearby, young (i.e. compact) SNR

^{44}Ti in Cas A, others?

The extent to which this science is achieved depends on the

field-of-view realized

For SNR, and certainly for searches and diffuse(?) emission

Accurate descriptions of many weak thermal lines (many

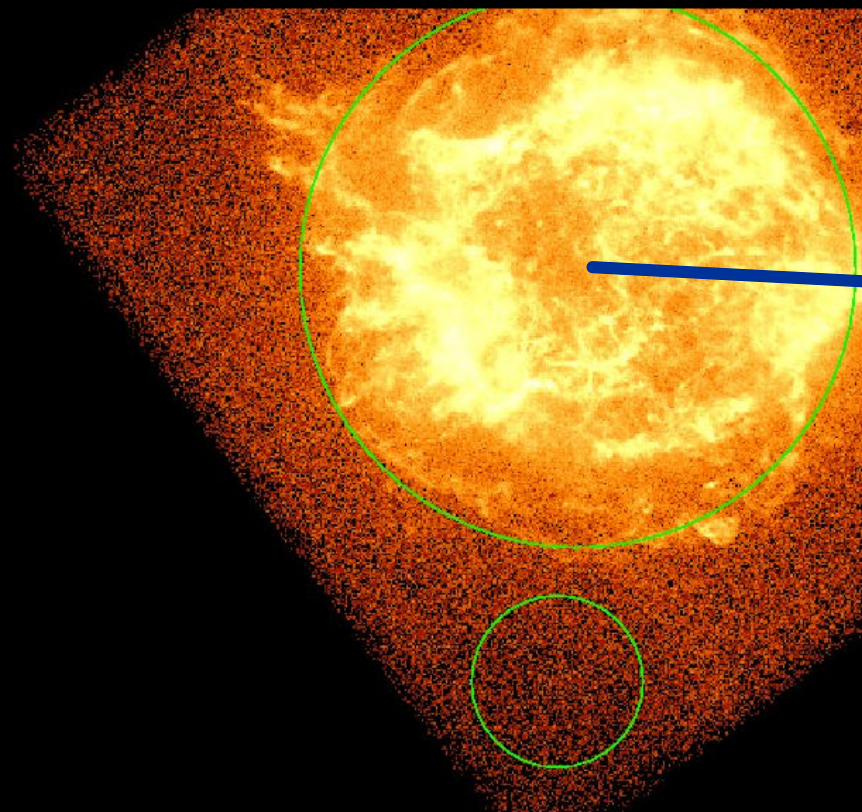
ionization states) will be needed to interpret these decay lines.

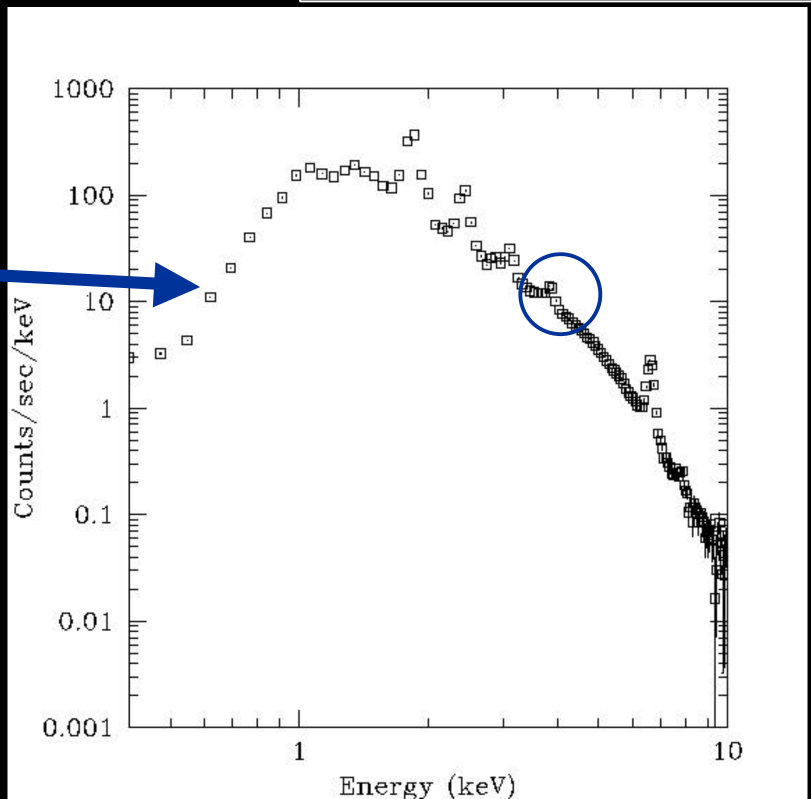
^{44}Ti decay X-rays from Cas A

K_α 4.1 keV (16.4%)

- ObsID 114, 2000/01/30
- 52 ksec ACIS-S

Ti44 63 y 0+ EC	Ti45 184.8 m 7/2- EC	Ti46 0+ 8.0
Sc43 3.891 h 7/2- EC	Sc44 3.927 h 2+ * EC	Sc45 7/2- * 100
Ca42 0+ 0.647	Ca43 7/2- 0.135	Ca44 0+ 2.086



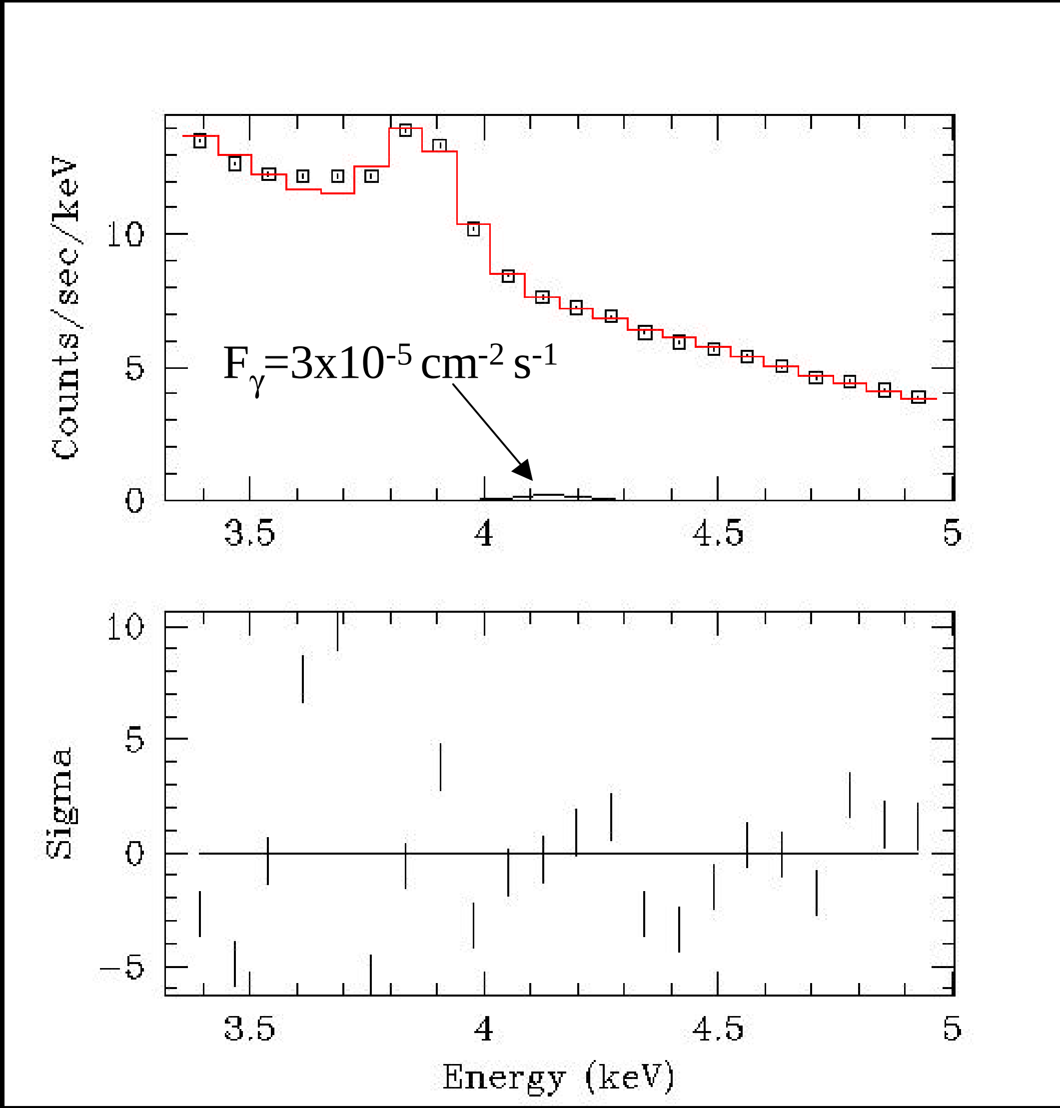


Chandra Cas A spectrum near Sc-K_α

- Strong continuum and Ca-K_α
- No evidence for ^{44}Ti decay, but

F(4.1 keV) < $2x10^{-5}$ cm^{-2} s^{-1}
99%

- Much more data available
- Eliminate bright knots? (For detection,makes yield measurement difficult.)



X-ray Spectroscopy Missions (@6keV)

	A_{eff} (cm^2)	ΔE (eV)	FOV(’)	$\Delta\theta$
ASCA-SIS	160	240	22	1’
Beppo-SAX	150		56	75”
Chandra ACIS	235	130	17	1”
XMM-Newton EPIC PN	850	130	30	6”
Constellation-X	*6600*	*2*	*2.5*	*15”*

Summary

- SN 1987A ^{55}Fe upper limit -- already surprising?
- Tycho's SNR ^{59}Ni limit -- close to expectations
- Cas A ^{44}Ti map -- not yet

Generally:

- No detections yet
- Current instruments might detect some isotopes
- Future instruments will --

  Larger areas, better energy resolution for bright sources

No ^{55}Fe Line?

- Lower A=55 nucleosynthesis yield
  but - intermediate temperature (T_9=3) must occur
  - some produced with ^{56}Ni (c.f. ^{44}Ti)
  - natural ^{55}Mn is made somewhere
- Higher optical depth
  slightly slower intermediate-Z zones can easily make τ(6 keV) > 1.

In Model 10hmm (Woosley & Pinto 1988), τ(6 keV) = 0.6 at 5000 days (from ^{55}Fe outward). Equal contributions from O, Si, S (mixing down to lower velocity enhances τ)

What is the optical depth of SN 1987A at 6 keV?

Woosley, Pinto, Hartmann

800 days⟶

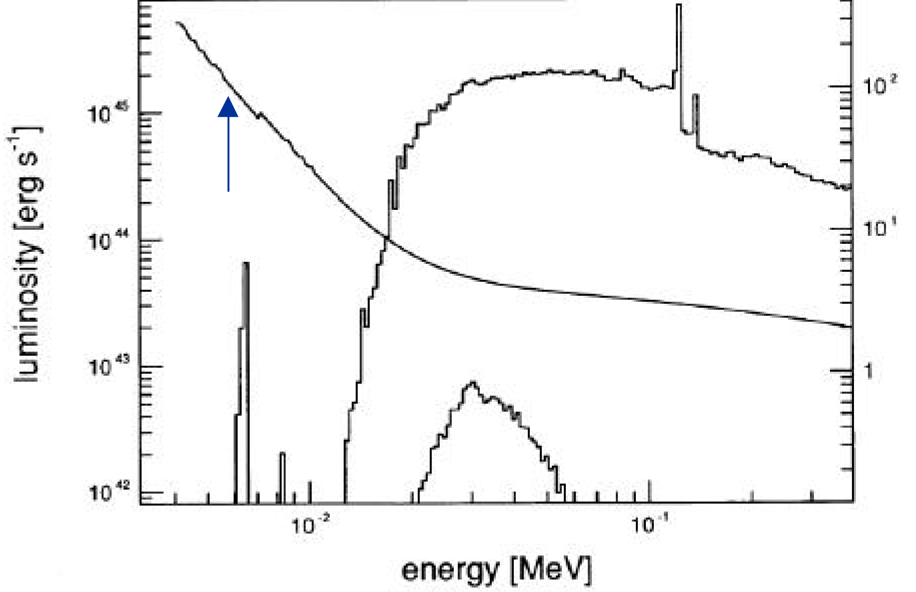
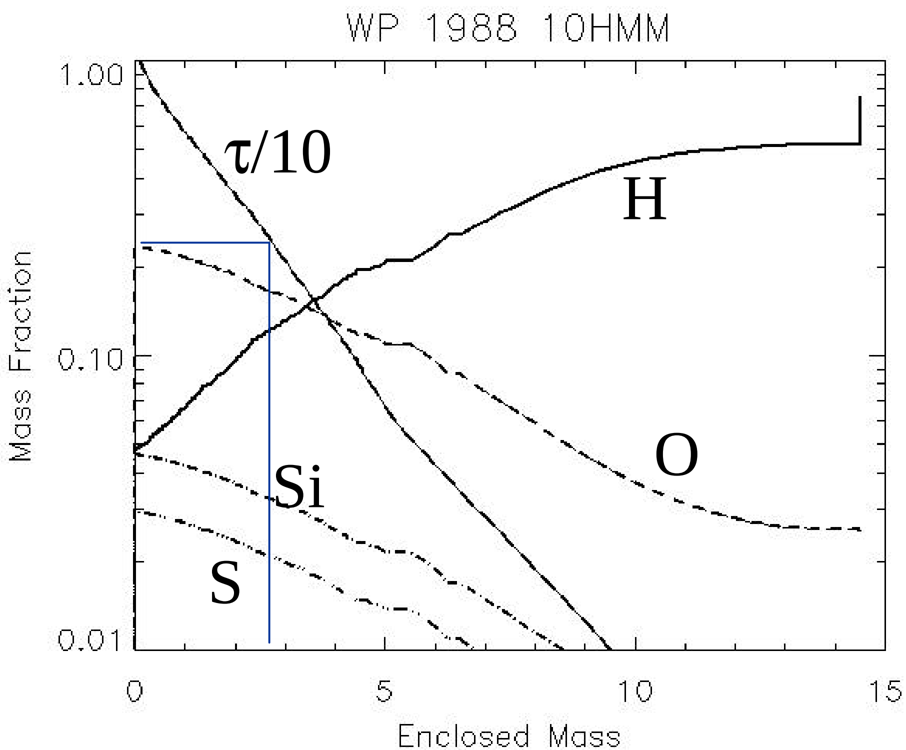


FIG. 5.—The modulation factor induced in the hard emission of SN 1987A by a central source shining with a luminosity and spectrum like that of an X-ray pulsator, Her X-1. Modulation would be best sought around 30 keV and might become apparent near day 1000 depending upon instrumental sensitivity. The bottom panel gives the "optical depth" as a function of energy on day 800. At later times the optical depth decreases as t^{-2}.

Woosley 10hmm
(private communication)



Other authors' models also give 6 keV optical depth of order unity.

How mixing is done matters.

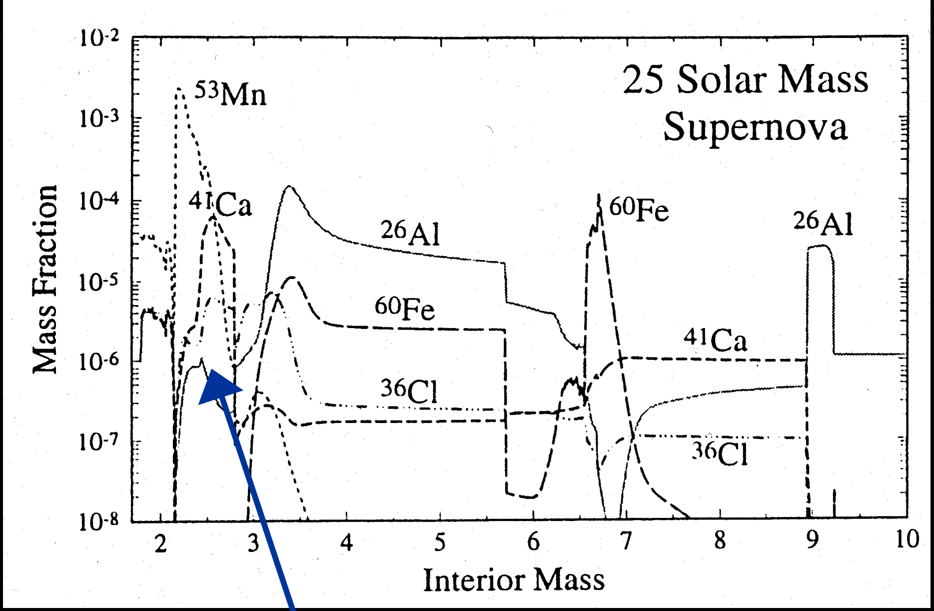
Conclusion -- SN 1987A

- ^{55}Fe line not seen at estimated level
- Might be explained by still thick (@6 keV) mantle
  - Implies good coverage early (c.f. Ginga obs)
  - We might wait quite awhile to see the compact object in X-rays
- Might still see it : more Chandra data
more XMM data
- Con-X et al. will struggle to overtake decay *if already thin*

^{53}Mn ($\tau_{1/2} = 3.7$ My)

K_α 5.406 keV (7.4%)

5.415 keV (14.6%)



- Source of ^{53}Cr in nature (made mostly as ^{53}Fe).
- Was present in forming solar system disk
- Core collapse SN, typically 3×10^{-4} $M_\odot$ from core.
- --> 27 $M_\odot$ in ISM (e.g., Woosley & Weaver 95)
- Type Ia's make more ($\geq10^{-3}$ $M_\odot$); (Nomoto et al.) possible bulge component also.
- Diffuse flux 1×10^{-4} cm^{-2} s^{-1} from central steradian.

Smoother than ----->